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Pattern and Process of Land Loss in the Mississippi Delta: A Spatial and Temporal Analysis of Wetland Habitat Change

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ABSTRACT: An earlier investigation (Turner 1997) concluded that most of the coastal wetland loss in Louisiana was caused by the effects of canal dredging, that loss was near zero in the absence of canals, and that land loss had decreased to near zero by the late 1990s. This analysis was based on a 15-min quadrangle (approximately 68,000 ha) scale that is too large to isolate processes responsible for small-scale wetland loss and too small to capture those responsible for large-scale loss. We conducted a further evaluation of the relationship between direct loss due to canal dredging and all other loss from 1933–1990 using a spatial scale of 4,100 ha that accurately captures local land-loss processes. Regressions of other wetland loss on canal area (i.e., direct loss) for the Birdfoot, Terrebonne, and Calcasieu basins were not significant. Positive relationships were found for the Breton (r^2 = 0.675), Barataria (r^2 = 0.47), and Mermentau (r^2 = 0.35) basins, indicating that the extent of canals is significantly related to wetland loss in these basins. A significant negative relationship (r^2 = 0.36) was found for the Atchafalaya coastal basin which had statistically lower loss rates than the other basins as a whole. The Atchafalaya area receives direct inflow of about one third of the Mississippi discharge. When the data were combined for all basins, 9.2% of the variation in other wetland loss was attributable to canals. All significant regressions intercepted the y-axis at positive loss values indicating that some loss occurred in the absence of canals. Wetland loss did not differ significantly from the coast inland or between marsh type. We agree with Turner that canals are an important agent in causing wetland loss in coastal Louisiana, but strongly disagree that they are responsible for the vast majority of this loss. We conclude that wetland loss in the Mississippi delta is an ongoing complex process involving several interacting factors and that efforts to create and restore Louisiana's coastal wetlands must emphasize riverine inputs of freshwater and sediments.

Introduction

From the 1930s until the present, there has been a dramatic loss of wetlands in the Mississippi Delta with estimates as high as 100 km^2 yr^{-1} (Gagliano et al. 1981), and a total area of about 3,900 km^2 of coastal wetlands has been lost (Boesch et al. 1994). Land loss rates were highest in the 1960s and 1970s and have declined since, although rates remain high (Baumann and Turner 1990; Britsch and Dunbar 1993; Barras et al. 1994) (note: in this paper, when we use the term land loss, it signifies

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wetland loss). An understanding of the causes of this land loss is important not only for a scientific understanding of the mechanisms involved but also so that effective management plans can be developed to recover these losses.

A number of factors have been linked to land loss, including elimination of riverine input to most of the coastal zone due to construction of flood control levees along the Mississippi River, altered wetland hydrology mostly due to canal construction, saltwater intrusion, wave erosion along exposed shorelines, a decline of suspended sediments in the Mississippi River, and high relative sea-level rise (RSLR—the combination of subsidence and eustatic sea level rise) (see Boesch et al. 1994 for a review of these issues). Many have concluded that land loss is a complex interaction of these factors acting at different spatial and temporal scales (e.g., Turner and Cahoon 1987; Kesel 1988, 1989; Day and Templet 1989; Boesch et al. 1994; Day et al. 1995, 1997).

Turner (1997) analyzed wetland loss in coastal Louisiana wetlands from 1932 to 1990 using statistical analyses of land to water changes in 15-min quadrangle maps. He concluded that virtually all of the loss was caused by canals, that land loss was near zero in the absence of canals, and that land loss rates declined to near zero by the late 1990s. Turner explicitly excluded saltwater intrusion and the leveeing of the Mississippi River as important factors contributing to land loss because land loss was highest near the coast and because regressions of direct versus indirect land loss had zero intercepts. In this paper and in Turner (1997), direct land loss refers to wetland which becomes water when canals are dredged and indirect land loss refers to all other wetland loss. Turner's conclusions contradict Penland et al. (1996), who concluded that about 46% of wetland loss in coastal Louisiana has occurred through natural processes.

The objective of this paper is to carry out a further evaluation of the causes of land loss in the Louisiana coastal zone, particularly with respect to the effects of canals.

Turner (1997) stated four hypotheses about the coast-wide causes of land loss and tested them with various statistical analyses of direct and indirect land loss rates from 15-min quadrangle maps which contain about 68,000 ha. We have incorporated the essence of these in the following hypotheses which we test in this paper. Direct land loss (i.e., due to canals) is quantitatively related to land loss in general, both for individual hydrologic basins and for the entire coast, indicating that most land loss can be attributed to canals. When direct land loss is zero, other land loss is close to zero (i.e., the intercept in regressions of other land loss on direct land loss is zero). Land loss is highest near the coast and decreases inland. This implies that land loss is highest in salt marsh and lowest in fresh marsh and that saltwater intrusion has not been an important factor in land loss. Restricted riverine input has had little impact on land loss. A corollary to this is that land loss in wetlands in the Atchafalaya Delta region, which is not leveed and receives approximately one third of the total flow of the Mississippi River, has been the same as that of other basins with similar density of canals. If land loss in the Atchafalaya delta region is low, it would suggest that while lack of riverine input may not have directly caused land loss, riverine input is essential to building new wetlands and reducing loss of existing wetlands.

The Study Area

The Mississippi Delta formed over the past 6,000–7,000 years as a series of overlapping delta lobes (Roberts 1997). There was an increase in wetland area in active deltaic lobes and wetland loss in abandoned lobes, but there has been an overall net increase in the area of wetlands over the past several thousand years. The coast has often been described in terms of a series of hydrologic basins that are separated largely by current or abandoned distributary channels (Louisiana Wild Life and Fisheries Commission 1971; Reed 1995; Fig. 1). Coastal wetlands of the Mississippi Delta consist of two physiographic units, the Deltaic Plain to the east and the Chenier Plain to the west (Roberts 1997). Active deltaic lobe formation took place in the deltaic plain, which is divided into six hydrologic units. These are, from east to west, the Pontchartrain, Breton, Birdfoot (Balize), Barataria, Terrebonne, and Atchafalaya basins. The modern mouth of the Mississippi, the Birdfoot delta, although not technically a basin, has been considered a separate hydrologic unit for most analyses of Louisiana coastal wetlands and we follow this convention in this paper. The Chenier Plain was created by a series of beach ridges and mud flats formed by periods of westward down drift of sediments. It is comprised of two hydrologic units, the Mermentau and Calcasieu/Sabine basins. The coast is also characterized by a series of vegetation zones (saline, brackish and fresh marshes, and freshwater forested wetlands, from the coast inland) that run roughly parallel to the coast and are determined primarily by salinity. Changes in these vegetation zones over the past half century have been described in a series of four vegetation maps (O'Neil 1949; Chabreck et al. 1968; Chabreck and Linscombe 1978, 1988). In this paper, we restrict our analysis to the coastal marshes.

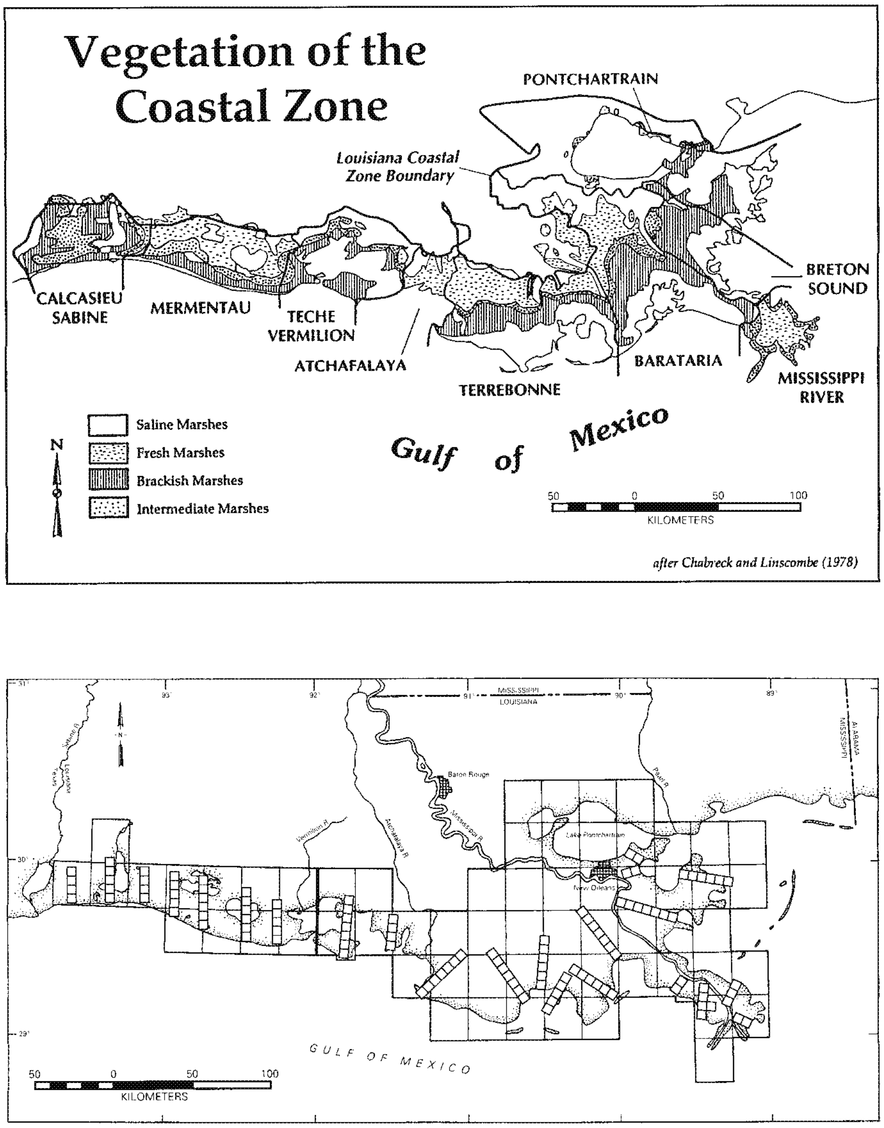


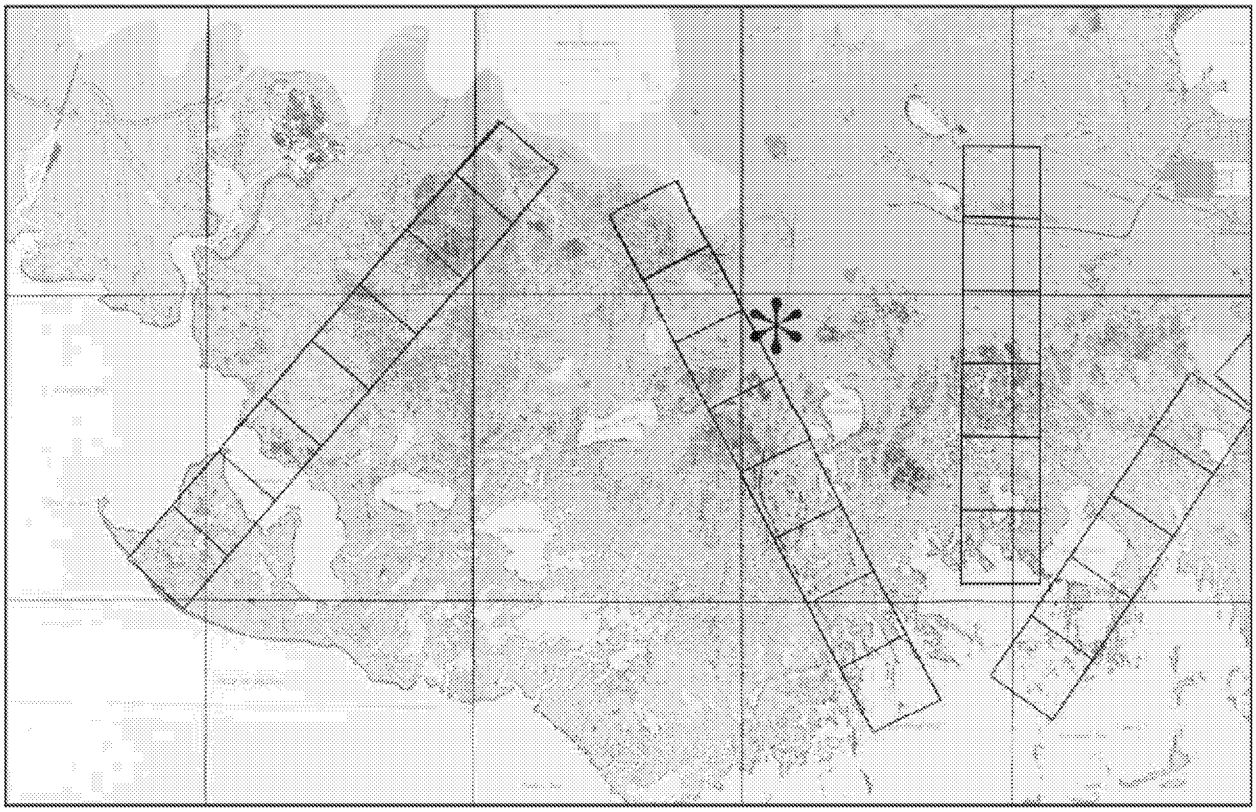
Fig. 1. Top panel: Map of the Louisiana Coastal Zone showing the location of the coastal hydrologic basins, marsh vegetation zones, and hydrologic features discussed herein. The Calcasieu Ship Channel runs north-south through Calcasieu Lake in the Calcasieu-Sabine basin and the Mississippi River Gulf Outlet runs through the center of the Breton Sound basin. Bottom panel: Location of the 15-min quadrangles on which Britsch and Dunbar (1993) aggregated land loss patterns discussed in this study and which Turner (1997) used for his analysis, and location of smaller sampling cells used to subsample the maps of Britsch and Dunbar.

Materials and Methods

Data Base

Britsch and Dunbar (1993) quantified wetland to water changes during four mapping intervals: early-1930s to mid-1950s (referred to in this paper as 1932–1955; the actual dates of the different maps used varied slightly), 1956–1973, 1974–1982, and 1983–1990. They aggregated their direct and indirect land loss data to the standard 15-min quadrangle map scale (~68,000 ha or 168,000 acres). This is a convenient scale for maps because it is large enough to present a considerable amount of detail but small enough so that the number of maps which encompass the entire coastal zone (about 50 maps) is not excessive. Britsch and Dunbar also produced six spatial maps that were color coded for each mapping interval (Britsch and Dunbar 1996; Fig. 2).

However, the 15-min quadrangle scale is generally too large for statistical analysis of site-specific patterns of wetland loss in coastal Louisiana. The patch size of most of the land loss that has occurred in the coastal zone is considerably smaller than the scale of a 15-min quadrangle. An exami-



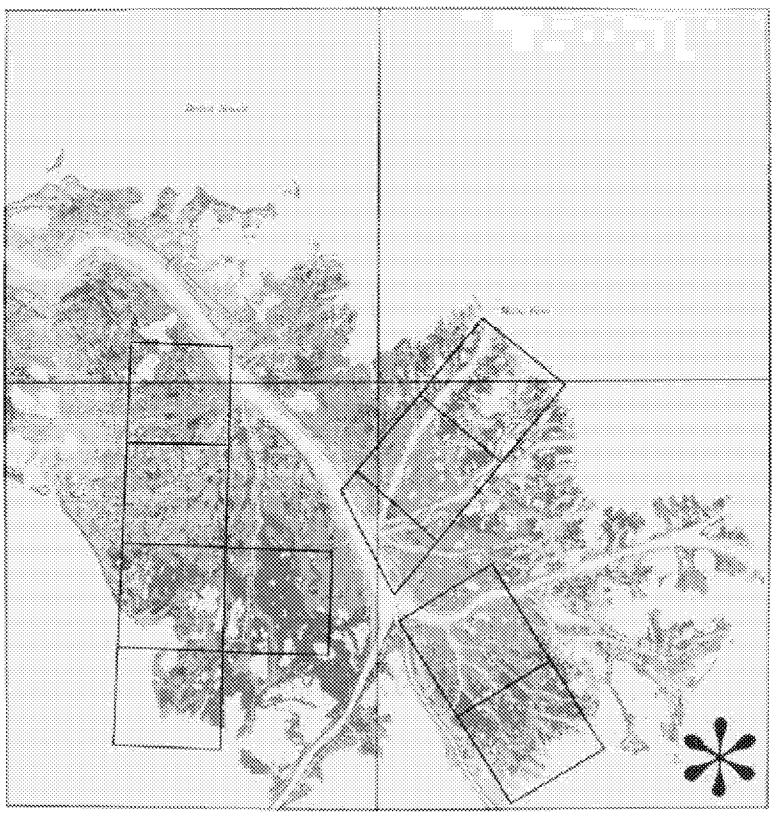


Fig. 3. The Britsch and Dunbar land loss map of parts of the Terrebonne and Barataria Basins overlaid with the 1978 vegetation map of Chabreck and Linscombe (1978). By overlaying successive vegetation maps on the land loss maps, the habitat type of the wetlands which were lost was determined. The different colors refer to land loss during different intervals (green: 1932–1956, orange: 1956–1974, red: 1974–1983, blue: 1983–1990). The center of the figure is approximately 90°30′W, 29°21′N.

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Fig. 2. Land loss maps of the Louisiana coastal zone from Britsch and Dunbar (1996) showing the 15-min quadrangle scale on which they organized the data and which Turner (1997) used for his analysis, and the cell locations for the subsampling for the analysis presented in this paper. The different colors refer to land loss during different intervals (green: 1932–1956, orange: 1956–1974, red: 1974–1983, blue: 1983–1990). Shown are examples from eastern Atchafalaya, Terrebonne, and western Barataria basins (top panel), and the Mississippi Delta basin (bottom panel). The asterisks show the Dulac (2A) and East Delta quadrangles (2B) which are discussed in the text. The asterisk in A is located approximately 91°W, 29°30′N. The center of the grid in B is located at 89°15′W, 29°15′N.

nation of the maps of Britsch and Dunbar (1993) shows that most 15-min quadrangles contain separate patches of wetland loss that are not spatially or functionally related to each other (see Fig. 2). For example, in a detailed study of the proximity of canals and wetland land loss (Leibowitz 1989), no relationship existed for land loss greater than 5 km from the canals.

Data Analysis

To better approximate the location and scale of many of the land loss processes and patterns (including oil and gas fields where most canals occur), we subsampled the maps of Britsch and Dunbar (1996) at a 4,100 ha (10,100 acres) or 6.4 × 6.4 km cell size (Fig. 2), which approximates the size of an average oil field network or a large marsh management impoundment (Cahoon and Groat 1990). A priori, the total number of cells (n = 121) was determined by budget constraints. These cells were arranged along 19 transects positioned nearly equidistant from each other, such that the number of cells per unit area of the coast was roughly equal. We did not include transects which would have been practically all water (e.g., transects in Lake Calcasieu or Lake Pontchartrain). However, to ensure that each basin received at least n = 7 cells, it was necessary to place some transects closer together (e.g., the birdfoot hydrologic unit is very narrow compared to the others). The transects were positioned perpendicular to the local coastline (either the Gulf shoreline or interior bay margins as in the Terrebonne, Barataria, Breton, and Pontchartrain basins) and varied in length because they extended to the inland extent of the mapped wetland, but did not overlap one another. While this process was not completely random, the placement of the transects was made without regard to overall land loss patterns and, once the coastal cell of each transect was placed, all cells along the transect were fixed in place.

In each cell, direct (due to canal dredging) and all other land loss (termed natural loss by Britsch and Dunbar 1996) was determined for each sampling interval. Since Britsch and Dunbar only classified changes from land to water, the change from marsh to spoil bank adjacent to each canal is not counted as loss. Britsch and Dunbar did not classify land loss by habitat type. To determine the wetland habitat type in each cell, we overlaid vegetation classification maps described above on the habitat loss maps (Fig. 3). For the 1932–1955 loss period, we used the 1949 map of O'Neil (1949). In a similar manner, for the 1955–1973, 1974–1982, and 1983–1990 loss intervals, we used vegetation classification maps for 1968 (Chabreck et al. 1968), 1978 (Chabreck and Linscombe 1978), and 1988 (Chabreck and Linscombe 1988), respectively.

Regression and ANOVA analyses were performed using the SYSTAT 6.1 general linear model. Specific hypothesis tests between direct land loss (i.e., due to canals) and other land loss include: 1) other land loss in the entire coastal zone and in each hydrologic basin is statistically related to direct land loss and 2) when direct land loss is zero, other land loss is zero; 3) land loss is highest near the coast and in salt marshes (for this test, distance from the coast was defined by the sequence of each cell in the subsampling transects); and (4) land loss in the Atchafalaya Delta hydrologic unit is not different from that in other hydrologic units. Hypotheses 1 and 2 were tested with regression models, whereas 3 and 4 were tested as separate one-way ANOVAs using basin, cell number in the transects, and marsh type as categorical variables.

We did not eliminate cells containing less than 15% land in 1933 as in Turner (1997) because this potentially creates two biases. First, by definition, these cells are located on shorelines where the primary cause of land loss is wave erosion. Penland et al. (1996) reported that about 35% of land loss was due to wave erosion. Second, very few oil field canal networks are located directly on the Louisiana coastline and hence elimination of coastal cells may improve the regression fit.

Log transformations of the dependent or independent variable, or both, were required in several instances when the data did not meet the criteria for parametric analysis and when relationships were curvilinear. Nonparametric regression was required for the Pontchartrain and Breton Sound data sets (Burkes and Dodge 1993). When data contained an observation with excessive leverage (i.e., > 0.55) the results are presented with and without that observation (Hair et al. 1998). For the Barataria, Atchafalaya, and combined data set, one observation required omission because it produced an excessive (> ± 3.0) studentized residual (Hair et al. 1998). Unless specified, differences were deemed statistically significant at $\alpha = 0.05$.

An attempt was made to analyze the data standardized to the amount of land present at each site in 1933 (as in Turner 1997). That is, the direct and other loss values were proportionalized to the amount of land in each cell at the beginning of the study. These data required an arcsine square root transformation to meet normality and homogeneity of variance assumptions (Sokal and Rohlf 1995).

Results

Regression

For all the data standardized to the amount of land present in 1933, no significant relationships

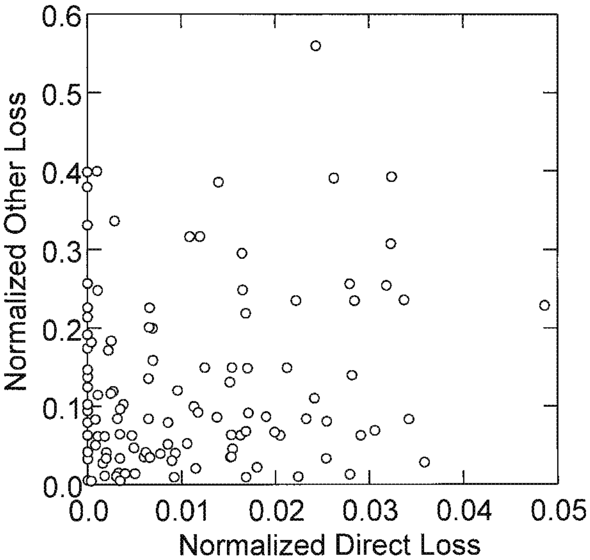

Fig. 4. Direct wetland loss and other wetland loss for all basins normalized to the land present in each quadrat in 1933 (as in Fig. 4 of Turner 1997) (n = 121).

occurred, regardless of transformation (Fig. 4). Interestingly, when cells were removed that contained less than 15% land in 1933 (see Fig. 4 of Turner 1997, for comparison), the fit did become marginally significant ($F_{1,113} = 4.16$, $p < 0.044$) albeit weak ($r^2 = 0.036$). For the analyses by basin, standardization did not improve the fits; therefore, all subsequent interpretations are limited to the non-standardized data.

Statistically significant relationships between other land loss and direct land loss were not obtained for the Birdfoot, Terrebonne, and Calcasieu hydrologic units (best fits producing $p \geq 0.12$, Fig. 5). Positive relationships existed for the Breton Sound ($F_{1,5} = 10.37$, $p = 0.023$, Fig. 6a), Barataria ($F_{1,22} = 56.97$, $p < 0.0001$, Fig. 6b), and Mermentau basins ($F_{1,20} = 10.73$, $p = 0.004$, Fig. 6c), producing $r^2 = 0.675$, $r^2 = 0.721$, and $r^2 = 0.349$, respectively. For the Barataria data set, omission of the single observation located on the y-axis (with leverage = 0.57, Fig. 6a) decreased the r^2 from 0.721 to 0.470. Interestingly, in the Atchafalaya, which is a basin characterized by high input of riverine inorganic sediments, a significant negative relationship existed between other wetland loss and direct loss ($F_{1,16} = 4.93$, $p = 0.041$, Fig. 6d), producing $r^2 = 0.361$. For the three parametric fits (Barataria, Mermentau, and Atchafalaya), the intercept (b_o) was statistically greater than zero, indicating that there was wetland loss in the absence of direct losses.

The regression of other wetland loss on direct wetland loss with all of the data combined could account for only 9.2% of wetland loss attributable to canals ($F_{1,118} = 12.00$, $p = 0.001$, $r^2 = 0.092$, Fig. 7). The intercept of $b_o = 644$ ha was highly significantly different from zero ($t = 6.60$, $p < 0.0001$).

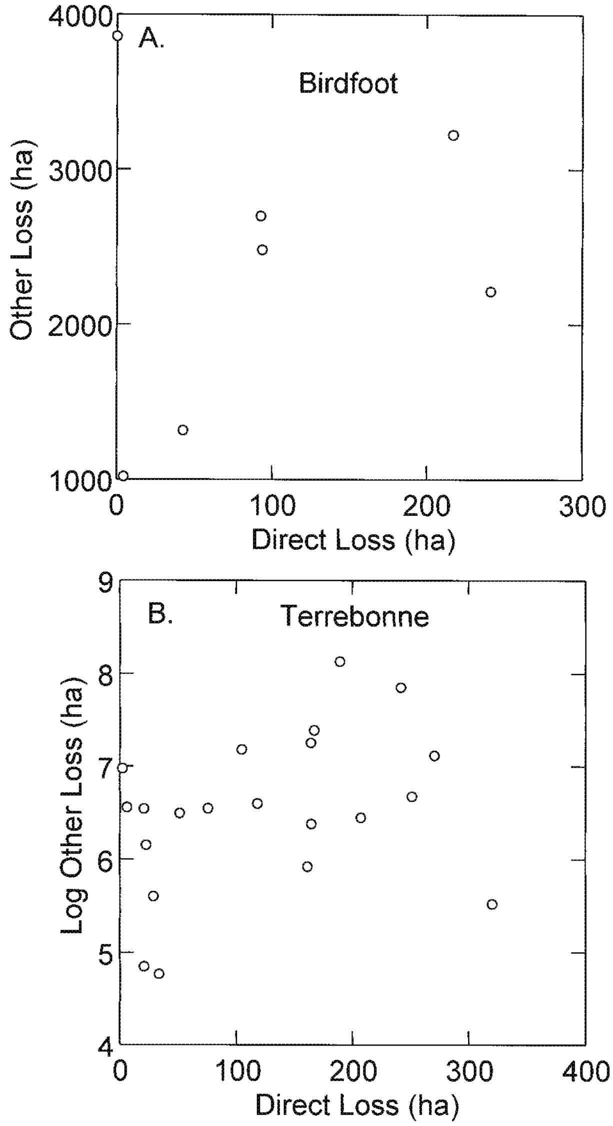

Fig. 5. Direct land loss and other land loss for the A) Birdfoot and B) Terrebonne hydrologic units from 1933–1990. Data for Calcasieu Basin are not shown as direct loss was zero for all quadrats.

ANOVA

The data set with all basins combined was also used to test for differences in other wetland loss from 1933 to 1990 due to effects of basins, the distance from the coast, and marsh type (Fig. 8). The basin effect was highly significant for the raw ($F_{7,112} = 9.56$, $p < 0.0001$, Fig. 8a) and standardized ($F_{7,111} = 8.71$, $p < 0.000$) data and the a priori linear contrast of the Atchafalaya versus other ba-

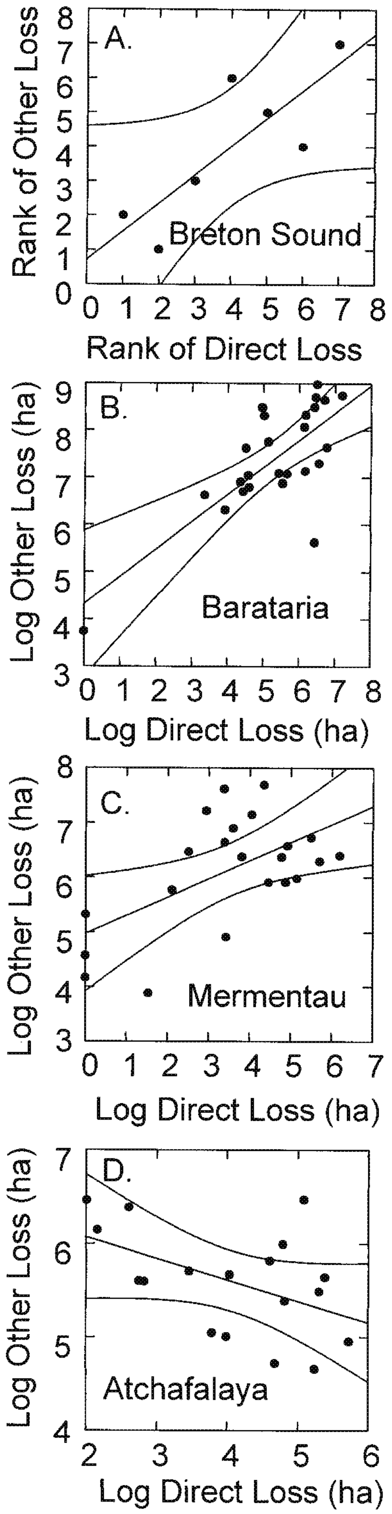

Fig. 6. Regressions of other wetland loss on direct wetland loss for A) Breton Sound, B) Barataria, C) Mermentau, and D) Atchafalaya basins from 1933–1990. 95% confidence intervals of the mean are included.

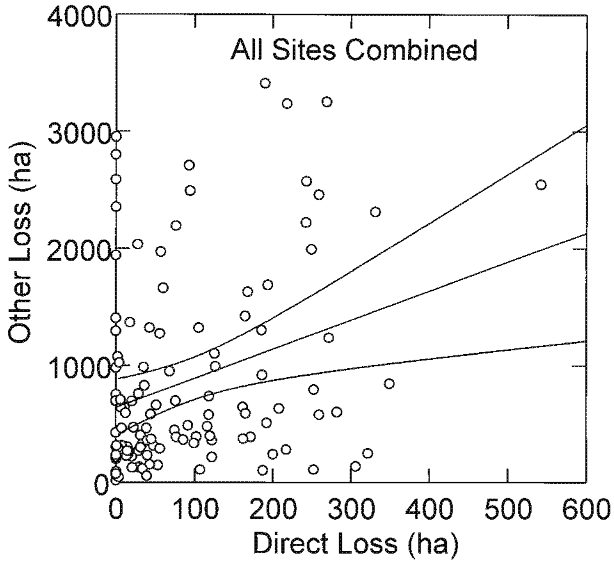

Fig. 7. Regression of other wetland loss on direct wetland loss for all hydrologic units combined for period of 1933–1990. 95% confidence limits of the mean are included.

sins was highly significant ($F_{1,112}$ = 12.97, p < 0.0001 and $F_{1,111}$ = 11.37, p < 0.0001 for the raw and standardized data, respectively), despite relatively low loss rates in the Breton Sound and Pontchartrain basins (Fig. 8a). Land loss did not differ from the coast inland for the raw data ($F_{7,108}$ = 1.32, p = 0.247), but did for the normalized data ($F_{7,107}$ = 2.68, p = 0.014) with the highest losses occurring in both coastal and the most inland cells (Fig. 8b). Wetland loss did not differ for different marsh types ($F_{2,169}$ = 2.72, p = 0.069), but displayed a similar pattern as that of distance from the coast (Fig. 8c).

Discussion

The results of our analysis indicate that canals have been an important factor in land loss, but that the relationship with land loss varies between basins. For Barataria Basin, up to 72% of other wetland loss was statistically associated with direct losses due to canals. However, omission of a single outlier decreased the r^2 to 0.47, or by 35%. From both an ecological and statistical perspective, we believe that a single observation with that much leverage warrants omission. There was no significant relationship between direct land loss and other land loss for several of the basins (Pontchartrain, Birdfoot, Terrebonne, and Calcasieu). This does not mean, of course, that land loss has not been caused by canals in these basins. Rather, it indicates that other processes are also important and mask the potential statistical relationship, or that insufficient statistical power existed due to low sample sizes.

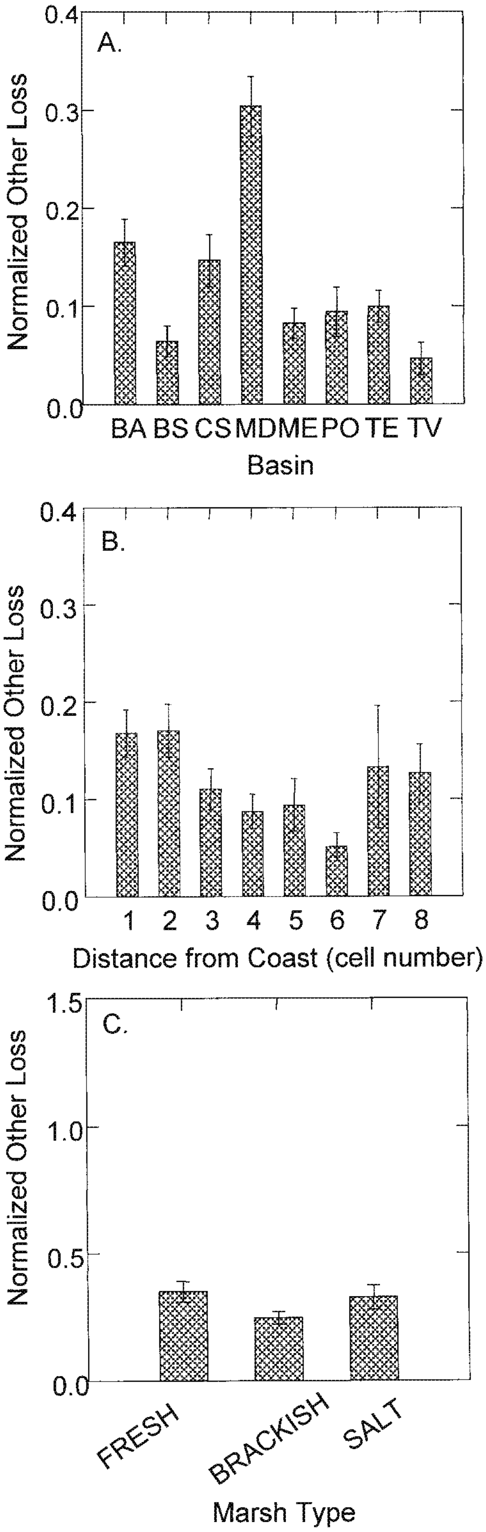

Fig. 8. Differences in wetland loss rates from 1933–1990 among A) basins, B) distance from the coast (cell 1 is nearest the coast), and C) marsh type. Standard error bars are included. For basins, BA is Barataria, BS is Breton Sound, CS is Calcasieu, MD is Mississippi Delta, ME is Mermentau, PO is Pontchartrain, TE is Terrebonne, and TV is Atchafalaya.

There was no clear pattern in land loss with distance from the coast or for different types of marsh, and in general the Atchafalaya hydrologic unit, with the highest riverine input, has had a significantly lower rate of wetland loss than the other basins. We address these findings in more detail in subsequent sections.

Mapping Scale

Although the 15-min quadrangle is a convenient mapping scale for a variety of purposes, it commingles (i.e., aliases) the functional processes responsible for coastal wetland loss in Louisiana. For example, the Dulac quad in the Terrebonne Basin (see Fig. 2a) contains shoreline erosion on the northern edge of Terrebonne Bay that is clearly functionally unrelated to canals, as well as other patches of land loss, some of which appear to be spatially related to canals and some of which do not. Likewise, in the East Delta quad of the Birdfoot Delta (see Fig. 2b), there are large patches of land loss to the north and south of North Pass. Direct land loss due to canals is relatively low in this area, yet it has one of the highest loss rates in the coastal zone. The causes for this land loss in the active delta are complex. Jetties have been in place since the last century on Southwest Pass and the river mouth is dredged annually. The channel is highly efficient and over bank flooding has been greatly reduced. The area has a high subsidence rate (Welder 1959; Fisk 1961; Gould 1970; Holdahl and Morrison 1974), and many of the marshes were floating at the time most of the loss occurred (between the 1932–1955 and 1956–1973 mapping intervals; O'Neil 1949; Chabreck and Palmisano 1973). Apparently, the immediate cause of the loss was the effects of two hurricanes destroying floating marshes (Chabreck and Palmisano 1973), but the changes in river management certainly contributed.

In a detailed study of the proximity of canals to patches of high wetland land loss, Leibowitz (1989) concluded that canals were not the primary cause of the loss. In addition, when positive relationships between canals and land loss existed, the relationship decomposed within 5 km of the canal. Our quadrats were 6.4 km on a side and therefore should have captured positive relationships crisply, had they existed.

The Role of Canals in Land Loss

We found that direct land loss (that is, dredged canals) ranged from being not statistically related to other land loss in several basins to accounting for 47% and 68% of the variation in other land loss in the Barataria and Breton Sound basins, respectively. Based on regression analysis, Turner

(1997) concluded that canals are responsible for the majority of wetland loss and that when direct loss is zero, other land loss is zero. Our analysis demonstrates that this is not the case. The scale of the 15-min quadrangles used by Turner leads to statistical relationships between canals and other land loss which is clearly unrelated to canals (i.e., shoreline wave erosion). Penland et al. (1996) also concluded that land loss was due to multiple interactive causes and indicated that about half of the land loss was natural and that the total amount of land loss indirectly due to submergence because of human modifications was about 35%. Among the causes of land loss other than canals were wave erosion and tectonic faulting.

In general, we found a lower overall statistical relationship between direct and other land loss than is suggested by the results of Penland et al. (1996). For the combined data set, the r^2 was only 0.092. One reason for this is that the relationship within each basin varies from linear to log-linear to log-log to no relationship to a negative relationship in the Atchafalaya Delta area. The process of wetland loss also differs between small-scale or local canal impacts and large-scale canal impacts. The small-scale impacts are the ones which Turner's and our work address. Large-scale canal impacts are often associated with deep navigation canals that directly connect saline and fresh areas (in a manner in which short canals do not) and lead to land loss which is, at least partially, related to saltwater intrusion, as discussed below. The Calcasieu Ship Channel and the Mississippi River Gulf Outlet are notable examples of this (Fig. 1, Morgan et al. 1958; Coastal Environments 1972). All considered, we believe that direct wetland loss due to canals accounts for greater than 9% of other wetland loss in coastal Louisiana; the minimum direct effects of land loss can be doubled to account for wetland loss due to spoil banks. Perhaps as much as half can be attributed to canals in some basins, which is the average for the three positive fits isolated herein (omitting the outlier in the Barataria data set). Penland et al. (1996) found that direct removal by canal dredging plus other human causes such as altered hydrology and substrate collapse, largely caused by leveeing the river and construction of canal spoil banks, was about 54% of total wetland loss.

An important detrimental impact of canal spoil banks is that they lead to the reduction of sediment input and poor drainage of marsh soils (Swenson and Turner 1987; Reed 1992; Boumans and Day 1994; Cahoon 1994; Cahoon et al. 1995b; Reed et al. 1997). The progressive waterlogging due to reduced sediment input can interact with existing salinity to produce deleterious effects on vegetation. A number of studies have shown that multiple stresses, such as salinity and waterlogging, have a much more detrimental impact on coastal vegetation than a single stressor (Grime 1979; Mendelssohn and McKee 1988; McKee and Mendelssohn 1989; Grace and Tilman 1990; Shaffer et al. 1992). A broad band of land loss in the Terrebonne and Barataria basins appears to be a result of such multiple stresses; this area corresponded to brackish and intermediate marshes that are spatially related to high canal densities (Fig. 3). Thus, it is possible that before any canals were dredged, the marshes in the brackish and intermediate zone of this area received enough sediment so that waterlogging was not excessive. After canals were dredged, the spoil banks likely decreased sediment input, which led to increased waterlogging and a salinity-waterlogging interaction causing vegetation death.

The Role of Saltwater Intrusion

We found no clear pattern in land loss rates with distance from the coast, or across different marsh types, suggesting that there is no general pattern of land loss across the salinity gradient. There are documented cases, however, where we believe saltwater intrusion was responsible for land loss. For example, huge marsh losses occurred west of the northern part of Lake Calcasieu during the 1956–1973 mapping interval. These losses occurred after the completion of the Calcasieu Ship Channel in 1941 and followed the passage of Hurricane Audrey in 1957. The hurricane apparently led to massive saltwater intrusion and widespread death of the freshwater *Cladium* marshes which previously occupied the area (Morgan et al. 1958). The remaining marshes are now intermediate to brackish. The construction of the Mississippi River Gulf Outlet (Fig. 1) led to saltwater intrusion and caused the death of almost all of the *Taxodium* swamps which formerly occurred east of the Mississippi River below New Orleans (Coastal Environments Inc. 1972). Some of this area is now open water, but much of the swamp has converted to *Spartina* marsh scattered with ghost cypress trunks.

Examples also exist of high land loss in freshwater areas that is clearly not attributable to saltwater impacts. The Turtle Bayou area in the northwestern Terrebonne Basin has experienced high rates of land loss (visible as a large orange and purple patch in the extreme upper left portion of Fig. 2a). In this area, which has remained fresh during all four mapping intervals, land loss has been variously attributed to extreme high water during the 1973 Mississippi River flood, burning of the marsh for management, excessive grazing by nutria, and a dense network of canals (Sasser personal communication).

The Role of Riverine Input in Land Building

Turner (1997) concludes that the isolation of most of the deltaic plain from riverine input by flood control levees has not played a significant role in wetland loss. This contradicts a long history of research that demonstrates how the river built and maintains the delta (Fisk et al. 1954; Kolb and Van Lopik 1958; Day et al. 1995, 1997; Roberts 1997). The most obvious example of this is the marshes in the Atchafalaya delta region, a non-leveed coastal bay where subaerial land building has continued since 1973 (Roberts et al. 1980). Our analysis demonstrates that land loss in this area is significantly lower than that of any of the other coastal basins. Turner cites Kesel's (1988) work indicating that only about 3% of the total sediment load of the Mississippi River flows overbank during floods, implying that riverine input to the deltaic plain is insignificant. This was for the period 1963–1983. Kesel (1988) also stated that 14% of the suspended sediment carried by flood flows flowed overbank. Moreover, Kesel (1988, 1989) indicated that crevasse splays (where overbank flow becomes concentrated in a well-defined channel with enough scour capacity to erode permanent or semipermanent breaks in the levee) are more important than overbank flow in delivering sediments to interdistributary wetlands. Kesel (1989, p. 183) concluded that both a reduction in suspended load by 70% from historic levels (1851–1895) and reduction in total overbank flow (including crevasse splays) due to levees were significant contributing factors in coastal wetland loss and suggested that "the most viable management strategy for the wetlands would be the diversion of sediment into selected areas where the land loss is most critical." Kesel et al. (1992) constructed a sediment budget for the lower Mississippi River for the period 1880–1911. They reported that below the Red River, about 26% of the sediment input was retained in the delta (6.2% in the Atchafalaya basin, 7.2% in channel storage, and 12.3% in overbank storage). At present, about one third of the Mississippi flows into shallow inshore areas via the Atchafalaya River. As a result of this sediment input, two new delta lobes are forming at the mouths of the Atchafalaya River and the Wax Lake Outlet (Roberts et al. 1980; van Heerden and Roberts 1980; Fig. 1). In addition, there is accretion and elevation gain that offsets relative sea-level rise (RSLR) in marshes surrounding Atchafalaya Bay (Baumann et al. 1984; Cahoon et al. 1995a). Riverine input to this area has maintained relatively high elevation marshes that drain well and are characterized by strong elevation gains and high soil strength (Kemp et al. 1999). This beneficial effect extends from fresh to saline marshes. Canals in this region stand out because there is little land loss associated with them.

In the past, riverine input into the deltaic plain was sometimes very high during spring floods. For example, in the great flood of 1927, flood control levees failed and much of the deltaic plain was flooded (Barry 1997). Similar widespread flooding in the delta has been documented for earlier floods (Kesel and Reed 1995). At Caernarvon (about 20 km downriver of New Orleans), the levee was breached during the 1927 flood for 3 mo and up to 9,500 $m^3 s^{-1}$ was discharged into adjacent wetlands where up to 30 cm of sediments was deposited (Day, unpublished data). In this same area, a controlled river diversion with a capacity of 200 $m^3 s^{-1}$ (8,000 cfs) has been operational since 1992. This area has healthy marshes, high accretion rates, and a net land gain (Villarubia et al. 1999). Lane et al. (1999) showed that nutrients introduced by the diversion were rapidly assimilated by the system. The Bonnet Carre Spillway, a flood control outlet on the Mississippi River north of New Orleans, has been opened seven times since its construction in 1930; wetlands in the spillway are healthy and there has been no land loss (Britsch and Dunbar 1993). This is in contrast to adjacent areas outside the spillway where vegetation is stressed and there have been high rates of land loss (Britsch and Dunbar 1993). On a smaller scale, for salt marshes in coastal Louisiana it has been shown, for the most part, that only streamside marshes are accreting at a rate which offsets RSLR and that this accretion is due to mineral sediment input (Hatton et al. 1983; Baumann et al. 1984).

Turner (1997, p. 11 and 9) suggests that there is a "need for much greater ecological understanding" of wetlands and that there is little appreciation of the role plants play in "dominating the accumulation of sediments through their contribution to soil organic matter below ground." We certainly agree on the need for further study on the functioning of these systems. But it has long been recognized that soil formation and accretion in much of the Mississippi deltaic plain is dominated by organic soil formation from root production and management suggestions have explicitly incorporated this function (Hatton et al. 1983; Templet and Meyer-Arendt 1988; Day and Templet 1989; Nyman et al. 1993; Cahoon 1994; Cahoon et al. 1995a; Day et al. 1995, 1997). Organic soil formation often accounts for 70–80% of accretion, but addition of mineral sediments results in stimulation of plant production and health. Mineral sediment addition, especially in river water, has several positive impacts on marsh plant communities. The mineral sediments add strength and bulk to the sediments, for example, and they carry nutrients that stimulate productivity and iron which complexes with sulfide phytotoxins. Freshwater also reduces salinity stress.

Temporal Trends in Land Loss Rates

Based on his analysis, Turner (1997) concluded that land loss rates in the coastal zone will be close to zero by the year 2000. But land loss rates continue to be high, with measured loss rates ranging from 65 to 91 km^2 yr^{-1} in the 1980s and the 1990s (Barras et al. 1994). In addition, landscape modeling results (Reyes et al. In press) and statistical projections based on past land loss rates (Suhayda personal communication) indicate that land loss rates will continue to be high over the coming decades. For his modeling, Turner used a second-degree polynomial regression to fit wetland loss over time and to extrapolate loss rates from 1991–1995. This type of regression can fit only a symmetric parabola, and extrapolation with polynomial regression in general is cautioned (Zar 1996).

Conclusions

We conclude that wetland loss in the Mississippi Delta is a very complex process and that loss is caused by a dynamic and interacting set of processes. We agree with Turner that canals have been, and continue to be, an important agent in contributing to this land loss. We disagree, however, that canals are responsible for a majority of the land loss and that land loss is zero when canal density is zero. The exclusion of sediments, freshwater, and nutrients of the Mississippi River from much of the coastal zone has eliminated a major land building and maintenance mechanism which historically counteracted many of the processes responsible for land loss and thus is a major factor in coastal land loss in Louisiana. We also agree that hydrologic restoration, specifically with reference to canal spoil banks, should be a necessary component of a holistic, integrated delta restoration plan. This alone, however, will have minimal impact if it is not coupled with reintroduction of river water. Mineral sediments will be generally necessary to rebuild and maintain the coast. It is not likely that removal of spoil banks will result in revegetation on a large scale. Several studies have shown that there is rapid loss of elevation of 10–15 cm when plant death occurs (Nyman et al. 1993; DeLaune et al. 1994; Kemp et al. 1999). In addition, soil strength in highly stressed, low elevation wetlands is very low and there is very little elevation gain even with high accretion rates (Cahoon et al. 1995b; Kemp et al. 1999). A number of actions can help reduce land loss, but only riverine input can lead to major creation of new land. This agrees with our fundamental understanding of how deltas function both spatially and temporally (Day et al. 1997; Roberts 1997). If Louisiana is ever to achieve no net loss of its coastal wetlands, we believe that it will be necessary to expand restoration strategies to include major river diversions.

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